Nano Vision, Vol.1 (3), 123-128 (2011)

Exotic Metamaterials: A review

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ABSTRACT

Engineered materials composed of designed inclusions can exhibit exotic and unique electromagnetic properties not inherent in the individual constituent components. These artificially structured composites, known as metamaterials, have the potential to fill critical voids in the electromagnetic spectrum where material response is limited and enable the construction of novel devices. Recently, metamaterials that display negative refractive index – a property not found in any known naturally occurring material – have drawn significant scientific interest, underscoring the remarkable potential of metamaterials to facilitate new developments in electromagnetism.

Keywords:
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1. INTRODUCTION

With the advancement of science and technology in the last few decades, the dream of science fiction writers have come to reality which includes space shuttles, internet etc. and the next big thing in this arena would be the practical realization of invisibility cloaks. It is seen that, nature and technology contain a number of cases where the phenomenon of invisibility is demonstrated to some extent. In order to proceed with our discussion of the range of schemes to obtain the desired invisibility effect, we first clarify what the word "Invisibility" really implies. Literally invisibility represents the state of an object staying in plain view of an observer without being seen. Invisibility can be grouped into various categories. One of them is referred to as Camouflage where an otherwise visible object can stay indiscernible from the surrounding environment due to similarities in colors and patterns. Another method of being undetectable is to prevent information about the object from reaching the detectors (like radars). The stealth technology which is usually accomplished by using absorptive surfaces along with special shapes and materials, all intended to reduce the cross-section of the object against particular sources. The ultimate version of invisibility is to make an object reflect no light and absorb no energy i.e. the object is given

same scattering properties as those of vacuum. This last method of invisibility is the eventual goal of cloaking devices.

To be completely effective, an invisibility cloak should operate at all wavelengths of electromagnetic radiation without absorbing light as that would betray the cloaked object as a patch of blackness. All materials interact with electromagnetic fields, including light. Therefore materials such as ordinary spectacle lens can control light and by altering say, the shape of the lens, light will be controlled differently. A lens merely bends light in a certain way and how light bends depends on the properties of the material of which the lens is made. When an electromagnetic wave enters the lens, its fields interact with the charges of the particles in the substance of which the lens is made. In turn, that interaction changes the speed or wavelength (or both) of the wave. The fields are the electric and magnetic both of which appear as coupled fields in Maxwell's equations. From the view point of an electromagnetic wave, the material it interacts with is describable only by its electric permittivity (μ) and its magnetic permeability (ϵ). Let us consider the possible alternatives of these materials:

Category 1: $\mu>0$, $\epsilon>0$, being most known materials, natural or otherwise.

Category 2: $\mu>0$, $\epsilon<0$, being materials not well investigated.

Category 3: $\mu<0$, $\epsilon>0$, also being materials not well investigated

Category 4: $\mu<0$, $\epsilon<0$, where these materials do not exist naturally (Metamaterials)

Metamaterials are man-made materials consisting of artificially structured units that are made from naturally occurring substances and usually (but not necessarily) arranged in a periodic fashion. These units sometimes called “meta-atoms” or “meta molecules”, are a delicate arrangement of two or more conventional materials with known bulk properties, although the character of the composite architecture can be quite exotic and distinct from all of its constituents.

The concept of Metamaterials was first given theoretically in 1968 by Victor Veselago in his revolutionary paper entitled” The Electrodynamics of substances with simultaneously negative values of ϵ and μ”[1]. Nearly all his predictions came true approximately thirty years later. At first Pendry and his colleagues theorized a practical way to obtain negative permittivity over a certain frequency range using periodic array of wires[1,2,3,11] and presented their study on the effective negative permeability and how the negative permeability can be realized physically2[,3]. Hence forth various studies have been done[14,16,17,18,19,20] in the last decade and practical use of metamaterials in technology have become possible to a great extent which includes remote aerospace applications, sensor detection and infrastructure monitoring etc. The purpose of this paper is to review the progress made so far in general and special emphasis has been given to Negative Refractive Index Metamaterials (NIM) also known as Double Negative materials(DNG) and the concept of invisibility cloaking devices using split ring resonators as constituent meta- atoms.

2. NEGATIVE REFRACTION

To have negative refractive index is the main criteria for metamaterials used in cloaking devices. In general, all materials found in nature have positive refractive index, a measure of how much electromagnetic waves are bent when moving from one medium to another.

In a classic illustration of how refraction works, the submerged part of a pole inserted into water will appear as if it is bent upwards towards the water's surface. If water exhibited negative refraction, the submerged portion of the pole would instead appear to jut out from the water's surface. Or to give another example, a fish swimming underwater would instead appear to be moving in the air above the water's surface.

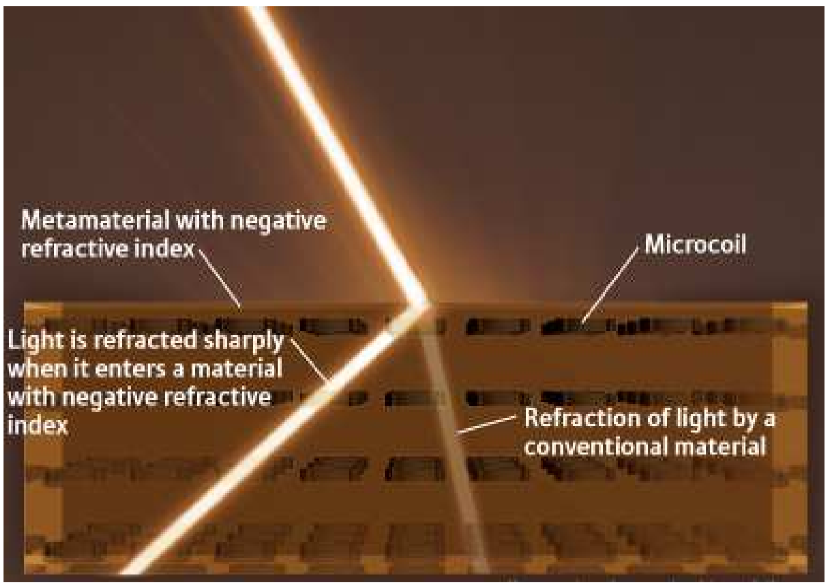

Fig. 1. Shown is schematic diagram depicting the phenomenon of negative refraction in case of a negative index metamaterial

The concept of negative refraction was discussed as far back as 1904 by Schuster in his book *An Introduction to the Theory of Optics* .He indicated that negative dispersion of the refractive index, n, with respect to the wavelength of light, λ, i.e. , $dn/d\lambda < 0$, could lead to negative refraction when light enters such a material (from vacuum), and the group velocity, v_g , *is* in the opposite direction to the wave (or phase) velocity, v_p. Although materials with $dn/d\lambda$ were known to exist even then (e.g., sodium vapor), Schuster stated that "in all optical media where the direction of the dispersion is reversed, there is a very powerful absorption, so that only thickess of the absorbing medium can be used which are smaller than a wavelength of light. With the

advances in material sciences, researchers are now much more optimistic 100 years later.

For a metamaterial to achieve negative refraction its structural array must be smaller than the electromagnetic wavelength being used and therefore to be effective in the visible range of the electromagnetic spectrum i.e. 400-700 nanometers its creation is a tough job. Again we know that natural materials do not respond to the magnetic component of light, but these artificial materials created does. Now, the consequences arising from a negative refractive index material are: The Doppler shift is reversed, Cherenkov radiation has its direction reversed, wavefronts move opposite in direction to the energy flow (anti-parallel time averaged Poynting vector) but Snell's Law applies in the usual way. Since one refractive index is positive (say air) and the other is negative (a MM), refraction will be reversed and be on the same side of the normal as the ray entered.

3. ELECTROMAGNETIC WAVE PROPAGATION AND CLOAKING

3.1 Theory

Trasformation optics is a simple approach to the design of MM's to alter the trajectories of electromagnetic waves passing through a volume of space, even though those trajectories conform to the local metric. Once the MM design is found, the co-ordinate transformation and its Jacobi matrix govern the transformation of Maxwell's equations. The altered (transformed) volume needs to be identical to a volume of free space if that replaced the transformation volume. With this method, anisotropy is required and any constraints placed on the MM used will reduce its performance for perfect invisibility cloaking (Pendry *et.al*, 2006)[3].

3.2 What Happens to light?

According to Fermat's Principle, light rays take the shortest optical paths in dielectric media and the refractive index, *n*, integrated along the ray trajectory defines the path length. When *n* is spatially varying the shortest optical paths are not straight lines and re usually curved. This light bending is the cause of many optical illusions, for example the desert mirage. Let us imagine a different situation where a medium guides light around a hole in it. Suppose that all parallel bundles of incident rays are bent around the hole and recombined in precisely the same direction as they entered the medium. An observer would not see the difference between light passing through the medium, propagating across empty space or, equivalently, in a uniform medium. Any object placed in the hole would be hidden from sight. Further theoretical work in this regard has been done by Leonhardt in 2006.

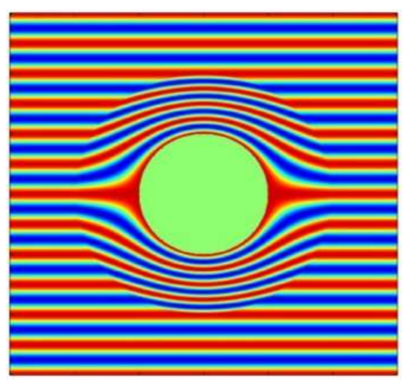

Fig2.Schematic diagram showing light bending around a cloaked object

4. SPLIT RING RESONATORS

In 1968, when Veselago theoretically investigated the electrodynamic consequences of a medium having both ϵ and μ negative, he pointed out substances with μ <0 were not available.Negative μ_{eff} (ω) has been shown to be possible when a polariton exists in the permeability such as in the antiferromagnets, MnF_2 and FeF_2, or certain insulating ferromagnets. However a negative permeability with losses coexisting with a negative a negative ϵ has not been demonstrated. The Split Ring Resonator medium recently introduced by Pendry[2] has now given the opportunity to make a material with negative permeability. A Split ring resonator (SRR) consists of an inner square with a split on one side embedded in an outer square with a split on the other side. The rings are made of non magnetic material and have a small gap between them. There are various types of SRR's eg.1-D Split Ring Structure, Symmetrical Ring structure, Omega structure etc. Smith et.al showed the first demonstrations using a composite medium based on SRR's. A magnetic flux penetrating the rings will induce rotating currents in the rings, which will produce their own flux to enhance or oppose the incident field (depending on the SRRs resonant properties). This field pattern is dipolar. Due to splits in the rings the structures can support resonant wavelengths much larger than the diameter of the rings. This would not happen in closed rings. The small gaps between the rings produces large capacitance values which lower the resonating frequency, as the time constant is large. The dimension of the structures is small compared to the resonant wavelength. This results in low radiative losses and very high quality factors.

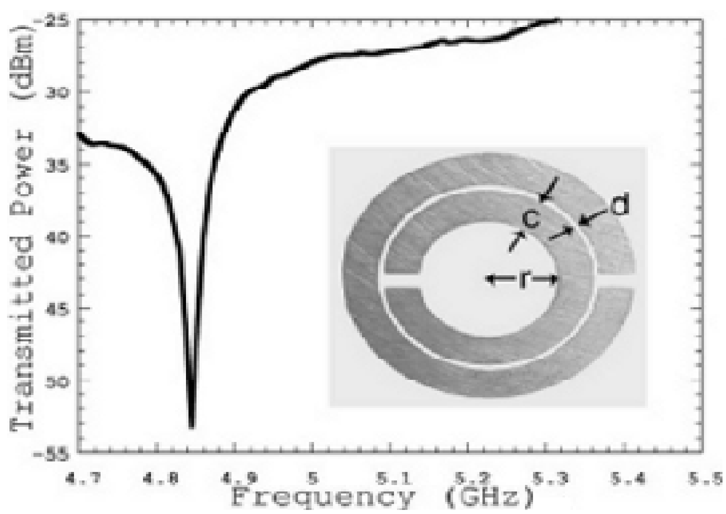

Fig. 3. Resonance Curve of an actual copper Split Ring Resonator c=0.8mm, d=0.2mm and r= 1.5mm. The SRR has its resonance at about 4.845 GHz and the Quality factor has been measured to be Q= $f_0/\Delta f_{3dB}$ >600, consistent with numerical simulations.

At frequencies below the resonant frequency, the real part of the magnetic permeability of the SRR becomes large (positive), and at frequencies higher than resonance it will become negative. This negative permeability can be used with negative dielectric constant of another structure to produce negative refractive index materials. A single copper SRR is shown in Fig. 3 with the dimensions indicated.

5. CONCLUSION

Here I have given a brief review of the present state of research in the field of metamaterials highlighting Negative Index Metamaterials (NIM) and their potential applications. I would like to add that using SRR's as component parts progress has been made to varying degrees in realizing practically ϵ, μ <0 especially in the microwave and infrared region. And though stress has been given on SRR's in this paper as it is the leading candidate, some progress has also been made using different structures.

REFERENCES

1. Veselago, V.G. *Sov. Phys. Usp*. 10, 509-514 (1968).
2. Pendry, J.B. *Phys. Rev. Lett*. 85, 3966-3969 (2000).
3. Pendry, J.B., Schurig, D. & Smith, D.R. Science 312, 1780-1782 (2006).
4. D. L. Mills and E. Burstein, Rep. Prog. Phys. 37, 817 (1974).
5. D. L. Mills, R. E. *Camley and Phys. Rev*. B 26, 1280
6. A. Hartstein, A. A. Maradudin, E. Burstein R. Brewer, and R. F.Wallis, *J. Phys*. C 6, 1266 (1973).
7. D. R. Smith, D. C. Vier, Willie Padilla, Syrus C. Nemat-Nasser, and S. Schultz, *Appl. Phys. Lett*. 75, 1425 (1999).
8. C.R. Simovski, *Physical Optics*. 107, 766-793.
9. D. R. Smith, D. C. Vier, Willie Padilla, Syrus C. Nemat-Nasser, and S. Schultz, *Phys. Rev. Lett*. 84, 4184-4187 (2000).
10. A. J. Holden, Pendry, J. B., , W. J. Stewart, and I. Youngs, *Physical Review Letters*, *Vol*. 76, 4773-4776, (1996).
11. A. J. Holden, Pendry, J. B., , D. J. Robbins, and W. J. Stewart, *IEEE Trans. on Microwave Theory and Techniques*, *Vol*. 47, 2075-2084, (1999).
12. C. Sabah, H.G. Roskos, Progress In Electromagnetics Research Symposium Proceedings, Moscow, Russia, August 18-21, (2009).
13. A. Grbic and G.V. Eleftheriades, *J. App. Phys*. 98, 43106 (2005).
14. D.R. Smith, *J. Opt. soc. Am. B* 21, 1032 (2004).
15. D.R. Smith, J.B. Pendry, *J. Opt. Soc. Am. B* 23 391 (2006).
16. P. K. L. Drude, Theory of Optics (Longmans, London, 1902; ONTI, Moscow, 1935).
17. I.E. Tamm, Z. *Phys*. 76, 849 (1932).
18. C.R. Simovski, Metamaterials 1, 62 (2007).
19. C.R. Simovski, Metamaterials 2, 342 (2008).
20. C.R. Simovski , *Phys. Rev. B* 62, 13718 (2000).